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SCOUR DOWNSTREAM OF A BLOCK RAMP IN ASYMMETRIC STILLING BASINS

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Block ramps are hydraulic structures generally used in mountains rivers. In the last decades they have become more common in river restoration as they minimize the environmental impact. Anyway, as other hydraulic structures, a scour hole forms at their toe which has to be foreseen and eventually controlled in order to avoid structural risks. The scour downstream of a block ramp in a stilling basin having the same width of the ramp was studied by many researchers who proposed relationships in order to evaluate the main geometrical parameters of the scour hole and ridge, but no studies are known in literature which analyze the scour mechanism downstream of a block ramp in an asymmetrically enlarged stilling basin. The aim of this study is to deepen the hydrodynamic behavior and the scour process in presence of two different asymmetrically enlarged stilling basin configurations. Tests were performed for block ramp slope 1V:8H and uniform stilling basin material. It was observed that a three dimensional scour hole forms downstream of the ramp toe when the channel bed has not the same ramp width. The maximum scour depth at equilibrium was compared to the respective ones that occurred in the same geometrical and hydrodynamic conditions in presence of stilling basin with the same ramp width. The scour depth was found much more prominent in the former case (asymmetric enlarged stilling basin) as the scour mechanism completely changes. A new useful relationship, taking into account also the effect of the downstream water level, is proposed in order to evaluate the maximum scour depth.

Key Words : *Asymmetric stilling basin, Block ramp, Hydrodynamic behavior, Tailwater.*

1. INTRODUCTION

Block ramps have been largely used especially in the last few decades in river restoration projects as they assure a high energy dissipation and contemporarily river bed stability. They are mainly used in mountain rivers and are made of blocks, whose mean diameters vary between 0.3 and 1.5 m, disposed on a steep bed. Generally their height is of several meters and the dissipative process takes place both on the ramp bed and in the stilling basin in which a scour hole forms. The stilling basin scour process is due to the erosive forces dissipated by vortices transporting the bed material downstream. A scour hole develops until a final equilibrium configuration is asymptotically reached (Sumer et al.[1]), Canepa and Hager[2]), Dey and Sarkar[3])).

Many studies are present in literature which analyze the scour mechanism and furnish useful relationships to foresee the maximum scour depth downstream of an hydraulic structure. Among these, Veronese[4]) was one of the pioneer who studied the scour phenomenon downstream of a spillway and gave empirical relations in order to evaluate the maximum scour depth. More recently, Hassan and Narayanan[5]) proposed a semi-empirical theory to predict the scour time rate for local scour downstream of an apron. Farhoudi and Smith[6]) analyzed the scour hole geometry downstream of hydraulic jump. A more detailed analysis for the scour process downstream of grade control structures was conducted by Bormann and Julien[7)] (and successively further developed by D'Agostino and Ferro[8)]) who derived equations for the main equilibrium scour hole parameters. Raudkivi and Breusers[9)] and Hoffmans and Verheij[10)] synthesized and collected many of the studies and results present in literature for scour downstream of hydraulic structures presenting practical guidelines to understand the phenomena related to scour which are useful for engineering practice. A theoretical approach based on momentum equation was developed by Hoffmans[11)]. He furnished equations to compute the maximum scour depth for both plunging and horizontal jets. Anyway, a more detailed analysis on both structural failure and scour mechanism related to block ramps can be found in recent literature. The former problem was investigated by Whittaker and Jäggi[12)] who analyzed the equilibrium condition of a ramp and the structural failure mechanisms. Pagliara and Hager[13)] analysed the scour mechanism downstream of block ramps for uniform bed material. The effect of channel bed material non-uniformity on scour mechanism was deepened by Pagliara[14)] who also analysed the jump type which can occur downstream of the ramp toe. Successively, Pagliara and Palermo[15), 16)] analyzed the effect of the introduction of rock-sills in the stilling basin on scour geometry in presence of both uniform and non-uniform stilling basin material, respectively and proposed some useful equations to evaluate both scour depth and length. Anyway, all the mentioned studies focus on the scour mechanism occurring downstream of a ramp toe in either protected or unprotected stilling basin, but limited to the case in which the ramp width is the same of the downstream stream reach. In all these cases a quasi two-dimensional scour hole forms.

The present paper aims to analyze the scour mechanism and the hydrodynamic behaviour in presence of an asymmetrically enlarged stilling basin downstream of block ramp in various tailwater condition, in clear water condition and when an F_{MB} jump type (free jump in mobile bed, see also Pagliara[14)]) occurs. Figs 1a-b-c-d illustrate a sketch of the model used for experiments in which the main geometrical parameters of the scour hole are shown (Fig1a) the various asymmetric tested configuration are schematized (Figs 1b-c-d).

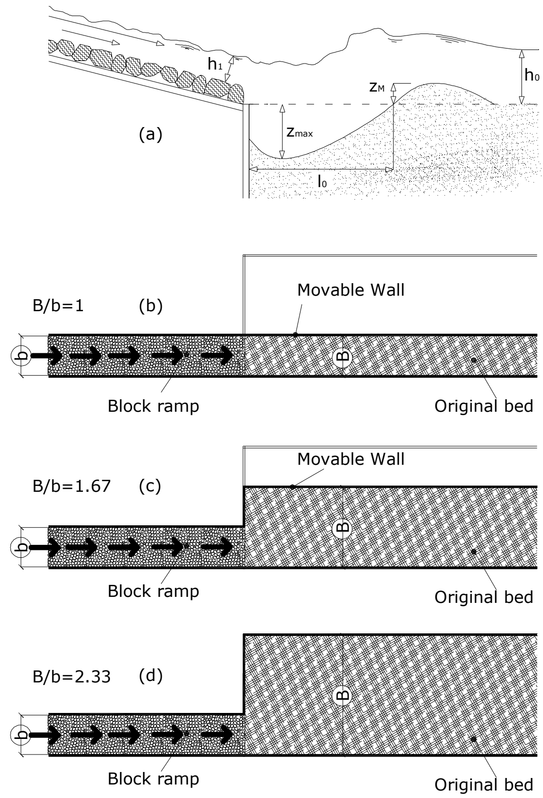

Fig.1 (a) Side view; diagram sketch of the experimental model with the indication of the main geometric parameters; plan view of the experimental model for (b) B/b=1, (c) B/b=1.67 and (d) B/b=2.33.

2. EXPERIMENTAL SET-UP

The experiments were conducted at the Hydraulic Laboratory of the University of Pisa, Italy. Tests were carried out in a rectangular channel 0.35 m wide, 6 m long and 0.50 m high. The ramps used in the experiments were made of inox steel sheet on which two different granular materials were glued in order to simulate ramp bed. Ramp width was 0.15 m. The material used for ramp bed were A1 and A2, whose granulometric characteristics are the following: $D_{50(A1)}$=0.02401m, $D_{65(A1)}$=0.02446m, $D_{90(A1)}$=0.02604m and $\sigma=(D_{84(A1)}/D_{16(A1)})^{0.5}$=1.11 for material A1 and $D_{50(A2)}$=0.01480m, $D_{65(A2)}$=0.01606 m, $D_{90(A2)}$=0.01786m and $\sigma=(D_{84(A2)}/D_{16(A2)})^{0.5}$=1.31 for material A2. D_{xx} represents the characteristic diameter of the ramp material for which xx% of sediment is finer and σ is the non-uniformity parameter.

For channel bed, one uniform granular material (m1) was tested. The granulometric characteristics of material m1 are the following: d_{16}=0.00435 m, d_{50}=0.00575m, d_{84}=0.00624m, d_{90}=0.00741m and

$\sigma=(d_{84}/d_{16})^{0.5}=1.2$, in which d_{xx} represents the characteristic diameter of the channel bed material for which xx% of sediment is finer. The methodology proposed by Hughes and Flack[17] was followed to measure the approach flow depth at the ramp toe h_1 (Fig 1a) on the rough ramp, where the virtual bed level was assumed $0.2D_{65}$ times below the mean top value of the rocks constituting the ramp material. One ramp slope was tested, 1V:8H corresponding to 0.125.

The effect of tailwater $T_w=h_0/h_1$, in which h_0 is the water level in the downstream part of the channel (after the ridge), was analyzed. A sluice gate was located at the downstream end of the channel in order to regulate the water level. In all the tests the jump is entirely located in the stilling basin and it never submerges the ramp. The flow discharge was measured with an electromagnetic flow meter located in the supply line.

Tests were conducted with three different basin enlargements, as shown in Figs 1b-c-d. The base tests are those tests in which the ramp has the same downstream channel width, i.e. $B/b=1$ (Fig. 1b), in which B is the channel width and b is the ramp width, which was fixed and equal to 0.15m. Then, in the same hydraulic and tailwater conditions tests were repeated for different channel widths, namely B=0.25m and B=0.35m, in order to highlight the differences in scour mechanism and in scour hole depth (Figs 1c-d).

Prior to each experiment the channel bed was carefully levelled and surveyed with a point gauge whose accuracy was 0.1mm (or $0.5d_{50}$). Then the water was discharged and after about 40 minutes, when the scour equilibrium was practically reached, the water levels h_1 and h_0 were measured and then the flow was stopped. The channel bed was surveyed again as to evaluate the maximum scour depth z_{max}, the maximum scour length l_0 and maximum ridge height z_M (see Fig. 1a).

3. RESULTS AND DISCUSSION

The analysis of the scour process in the case in which the width of the channel is the same of the ramp was conducted by Pagliara[14]. The author studied the phenomenon in presence of different graded stilling basin materials and when a F_{MB} jump type occurred downstream of the ramp toe. However, in his study the tailwater effect (h_0/h_1) was not taken into account as all the tests were performed in free flow conditions, meaning that no regulation of the water level h_0 was imposed (i.e. the sluice gate at the downstream end of the channel was left completely opened). Pagliara[14] found that the maximum non dimensional scour depth $Z_{max}=z_{max}/h_1$ is function of the ramp slope, the densimetric Froude number and the non uniformity parameter σ:

$$Z_{\max} = f(F_{dxx}, i, \sigma) \qquad (1)$$

in which F_{dxx} is the densimetric Froude number, $F_{dxx}=v_1/(g'\cdot d_{xx})^{1/2}$, $v_1=Q/(Bh_1)$ is the average approaching flow velocity, Q is the water discharge, B is the channel width (i.e. also ramp width in this case), $g'=[(\rho_s-\rho)/\rho]g$ is the reduced gravitational acceleration, ρ_s is the channel bed sediment density, ρ is the water density, g is the gravitational acceleration, d_{xx} is the channel bed sediment diameter, in which the subscript xx is a number that indicates the percentage of finer, i is the ramp slope and σ the non uniformity parameter.

In the present paper also the effect of tailwater was taken into account and it was observed that it is prominent. In fact, in the same hydraulic condition the scour depth results to be less if tailwater increases. The increase of downstream water level in fact increases the length of flow diffusion in the scour hole resulting in reduced hydrodynamic forces acting on the bed (see also Hoffmans[10] and Bormann and Julien[7]). Therefore, by applying the Buckingham Π-theorem and rearranging the non-dimensional parameters yields:

$$Z_{\max} + T_w = \frac{z_{\max} + h_0}{h_1} = f(F_{d90}) \qquad (2)$$

Functional relation (2) is valid in the case in which the width of the channel is the same of the ramp ($B/b=1$), and the parameters σ and i present in the functional relation (1) are not taken into account as only one uniform material and one ramp slope were tested. If one considers the case in which the channel is asymmetrically enlarged another non dimensional parameter has to be included in the functional relation (2) resulting in:

$$Z_{\max} + T_w = \frac{z_{\max} + h_0}{h_1} = f(F_{d90}, B/b) \qquad (3)$$

in which the parameter B/b takes into account the effect of the different widths.

It was observed that the effect of the enlargement on the scour geometry and on the hydrodynamic of the phenomenon is very prominent. In fact the scour mechanism and its shape completely changes. When

B/b=1 the scour hole has a regular and symmetric shape, moreover the scour results to be almost two dimensional, meaning that, especially for high discharges, the maximum scour depth is very close to the average depth evaluated in the transversal section in which the maximum scour occurs. Vice versa, if we consider the asymmetric enlarged channel, the scour hole results to be strongly three dimensional, as shown in Fig 4. This is due to the fact that the sudden enlargement determines a deflection of the flow pattern downstream of the ramp toe. In fact, observing Fig. 3, it appears evident that an almost circular ridge forms, which constitutes an obstacle for flow passage which is partially re-directed toward the ramp toe (zone of inverted flow).

Fig.2 Plan view of an experimental test with B/b=1.67 (flow from upstream)

In this zone a counter clockwise water circulation takes place and this leads both to a deflection and a concentration of the water flow exiting from the ramp toe, resulting in an increase of the erosive water capacity.
In all experiments, in fact, it was noted that, in the same hydraulic conditions the effect of enlargement is to increase the scour depth.

Basing on these observations and on dimensional analysis, the non dimensional group $Z_{max}+T_w$ was plotted versus F_{d90} for different ratios B/b (see Fig. 5).

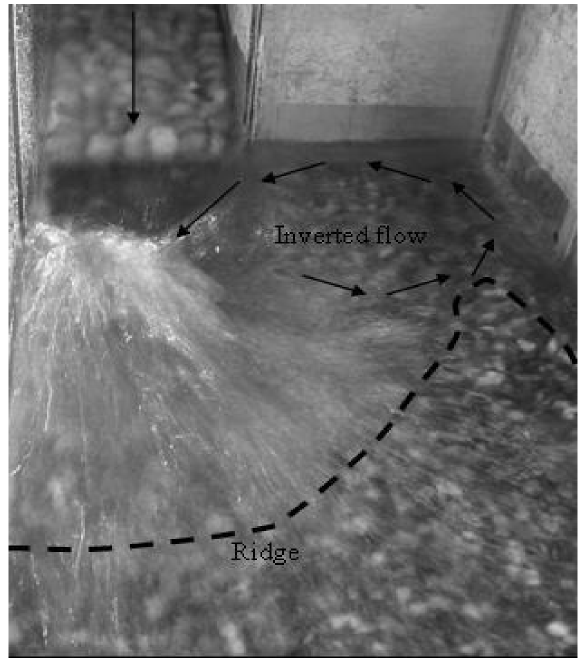

Fig.3 Plan view of an experimental test with B/b=2.33 with the indication of the hydrodynamic of the phenomenon (flow from upstream)

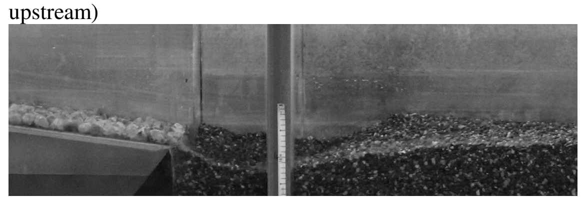

Fig.4 Side view of the experimental model (B/b=1.67)

It can be noted that, in the tested range, $Z_{max}+T_w$ is a monotonic increasing function of F_{d90}; moreover, in the same hydraulic conditions (i.e. for the same value of F_{d90}), $Z_{max}+T_w$ increases if B/b increases. The following general equation is proposed to evaluate $Z_{max}+T_w$:

$$Z_{\max} + T_w = \frac{z_{\max} + h_0}{h_1} = A\exp(CF_{d90}) \qquad (4)$$

in which A and C are coefficients depending on B/b that can be expressed as follows:

$$A = 0.14\frac{B}{b} + 2.31 \qquad (5)$$

and

$$C = 0.1\frac{B}{b} - 0.04 \qquad (6)$$

Substituting Eq. (5) and Eq. (6) in Eq. (4) one can evaluate $Z_{max}+T_w$. Eq. (4) is valid in the tested ranges of parameters, $2.5<F_{d90}<4.5$, $1.15<T_w<2.5$, $1<B/b<2.33$, for ramp slope i=0.125 and when the jump is completely located in the stilling basin, without submerging the ramp. A simple analysis of the proposed Eq. (4) shows that if F_{d90} is constant and the tailwater level increases, the non dimensional maximum scour decreases thus confirming the experimental tests and the prominent effect of tailwater level on scour mechanism. Fig. 6 compares the measured and calculated values of $Z_{max}+T_w$.

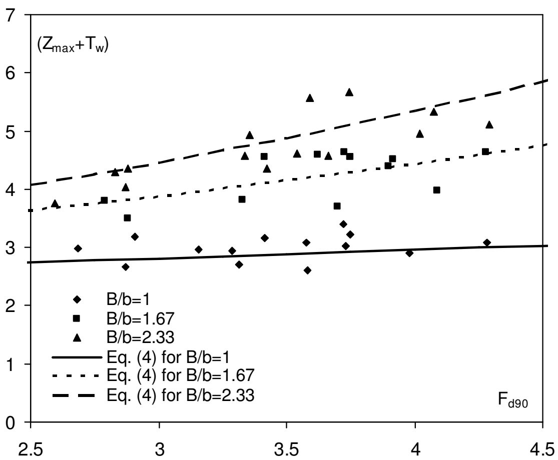

Fig.5 ($Z_{max}+T_w$) versus F_{d90} for B/b=1, B/b=1.67 and B/b=2.33

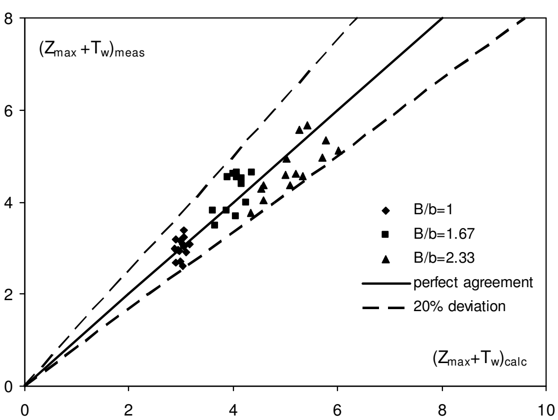

Fig.6 Comparison between measured and calculated values of ($Z_{max}+T_w$) for B/b=1, B/b=1.67 and B/b=2.33

It can be noted that the general equation proposed (Eq. 4) well predicts the parameter $Z_{max}+T_w$ as the calculated values are within a range of 20% deviation from the perfect agreement line.

5. CONCLUSIONS

In the present paper the scour mechanism downstream of a block ramp in an asymmetric stilling basin was analyzed. Experiments were performed in three different channel configurations (B/b=1, B/b=1.67, B/b=2.33). and with different tailwater levels. It was observed that, being the same hydraulic conditions, the hydrodynamic of the phenomenon completely changes in an enlarged stilling basin. An inverted flow zone forms in the enlarged side downstream of the ramp toe. The water flow exiting from the ramp is deviated and concentrated thus contributing to increase its erosive capacity. The scour depth, in fact, results to be more prominent than in the case in which B/b=1 and, in the tested range, it was observed that bigger is the channel width bigger is the scour depth. On the other side, a tailwater increase causes a reduction of the scour depth. This is due to the fact that the diffusion length of the flow coming from the ramp is bigger for high tailwater thus causing a reduction of the water erosive force when it impacts the stilling bed. A novel relationship is proposed to evaluate the non dimensional parameter $Z_{max}+T_w$ which results to be a function of the densimetric Froude number and the ratio B/b. Further experiments can be done in order to investigate both the effect of the non uniformity of the stilling basin material and the ramp slope.

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